Generation, Propagation, and Dissipation of Internal Solitary Waves

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LONG-TERM GOALS

Understand the dynamics of oceanic internal solitarylike waves; describe their generation, propagation, and dissipation in both continental shelf and sill bathymetry.

OBJECTIVES

1. Carry out a descriptive study of the large-scale characteristics of internal solitons at sites around the world, with the production of a global atlas being the output.
2. Expand the dnoidal model for internal solitons.
3. Apply the two-dimensional dnoidal model to SAR images of Gibraltar.
4. Perform analyses of selected existing imagery in U.S. data archives

APPROACH

The general approach is to analyze satellite imagery in conjunction with such field data as may be available, in order to understand the dominant characteristics of the solitons. The total data set is then used to guide the production of an analytic model of the propagation phase, and descriptive models of the generation and dissipation phases. Both existing and future imagery will be used. The investigation is being carried out in cooperation with Drs. Marshall Orr and Steven Finette of NRL, James Lynch and Tim Stanton of WHOI, Mohsen Badiey of the University of Delaware, and Peter Worcester and Bruce Cornuelle of Scripps.

WORK COMPLETED

1. *Carry out a descriptive study of the large-scale characteristics of internal solitons at sites around the world,* with an atlas being the output. Published reports have been surveyed, imagery and photographs from a variety of sources gathered, and a compilation of in-situ data made. Historical density data for the time and place of each image analyzed is taken from the archives and used to estimate the parameters from a continuously stratified fluid. The dnoidal theory is used to estimate the amplitudes. The results are being assembled into an atlas that can be updated as required, and which will include images and characteristics for the sites surveyed. CDROM versions will be made and distributed to interested scientists and to Naval facilities and ships. A World Wide Web FTP site has been constructed to present examples of the data on-line. An abbreviated version of the atlas will be published in the scientific literature.

2. *Expand the dnoidal model for internal solitons*. At present, this analytic model generates, propagates, and attenuates regular solitons on the continental shelf up to a region where the pycnocline depth is about half the total water depth. In more shallow water, the waves go through a transition that causes them to become upgoing rather than downgoing, while accompanied by major attenuation. The generation process near sills seems to be similar to lee-wave excitation on the offshore phase of the barotropic tide. Output will be two or more detailed papers on the application of the dnoidal model to actual oceanic data from SWARM, GLOBEC, and Gibraltar; this will allow a tuning of the model parameters with realistic data. The present state of the code is that the propagation/ attenuation programming is complete, and a solver is complete for internal eigenvalues and eigenfunctions that includes the effects of density stratification and shear flow. Singularities in the water column, where the wave speed equals the background current and critical layers are approached, cannot be handled by this method.

3. *Apply the two-dimensional (r, z) dnoidal model to Gibraltar*, using (a) density and current data from the Scripps tomography experiment (Worcester et al.) and (b) SAR imagery from ERS 1 and 2. A proposal to the European Space Agency for acquiring existing ERS-1/2 SAR imagery of Gibraltar was approved, and 40 images have been received. Profs. Ewe Send of the University of Kiel and Michel Crepon of the University of Paris will be cooperating investigators in the future.

4. *Perform an analysis of selected existing SAR images in U.S. data archives* for the small-scale properties of individual wave packets and the background internal wave field surface signatures. Attempt to relate the signature spectrum to the underlying amplitude spectrum using the theory of surface signature formation by internal currents.

RESULTS

The dnoidal model predicts, with reasonable fidelity, the dominant characteristics of the continental shelf solitons as regards evolution in time and space, waveforms, number of solitons, nonlinear and linear phase speeds, and attenuation. Figure 1 shows a predicted waveform for the solibore, which is given analytically as:

$$\eta(x,z,t)=\eta_0 W_{k_0}(z)\left\{2\,\mathrm{dn}_s^2\left[\frac{1}{2}k_0\left(x-Vt\right)\right]-\left(1-s^2\right)\right\}I(x,t)\,.$$

Here • (*x, z, t*) is the wave amplitude, $W_{k_0}(z)$ is the vertical structure function, $k_0 = (\bullet\ \bullet\ _0/6\bullet\ )^{½}$ is the characteristic wave number that relates wavelength to amplitude $\bullet\ _0$ and which allows estimation of the subsurface amplitude from surface imagery; and $\mathrm{dn}_s(x)$ is the dnoidal Jacobian elliptic function. The dnoidal function gives the baroclinic response of the system to a jump discontinuity at the shelf break. As it propagates toward shore, every B-V period it adds another oscillation to the waveform.

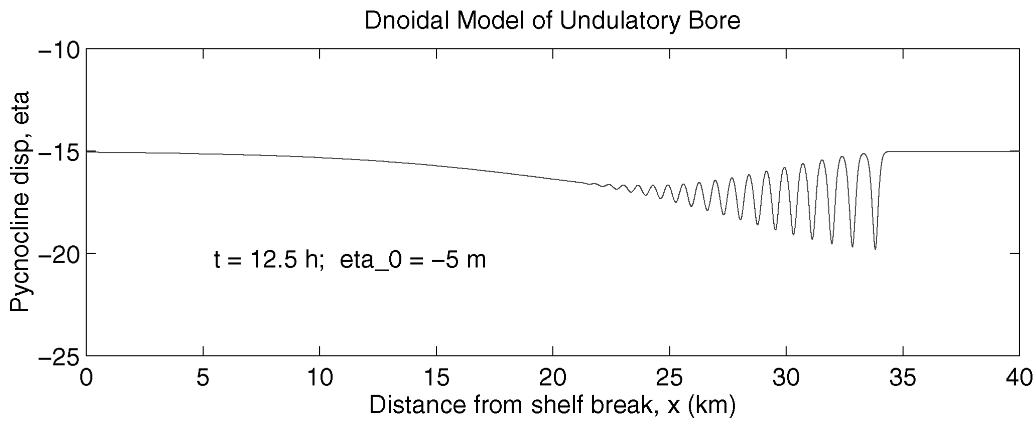

Figure 1. Waveform of dnoidal model showing undulatory bore character.

The nonlinear parameter $0 \le s^2 \le 1$ changes throughout the packet, causing variations of amplitude and number of solitons in the packet. The remainder of the baroclinic tidal cycle is described by the function $I(x,t)$; an attenuation factor is included in it. This function brings the amplitude back to equilibrium values before the onset of the next semidiurnal cycle of the solibore. Each of the wave packets visible in Fig. 2 below is described by the form of the amplitude function above, and each has its own nonlinear propagation speed, V.

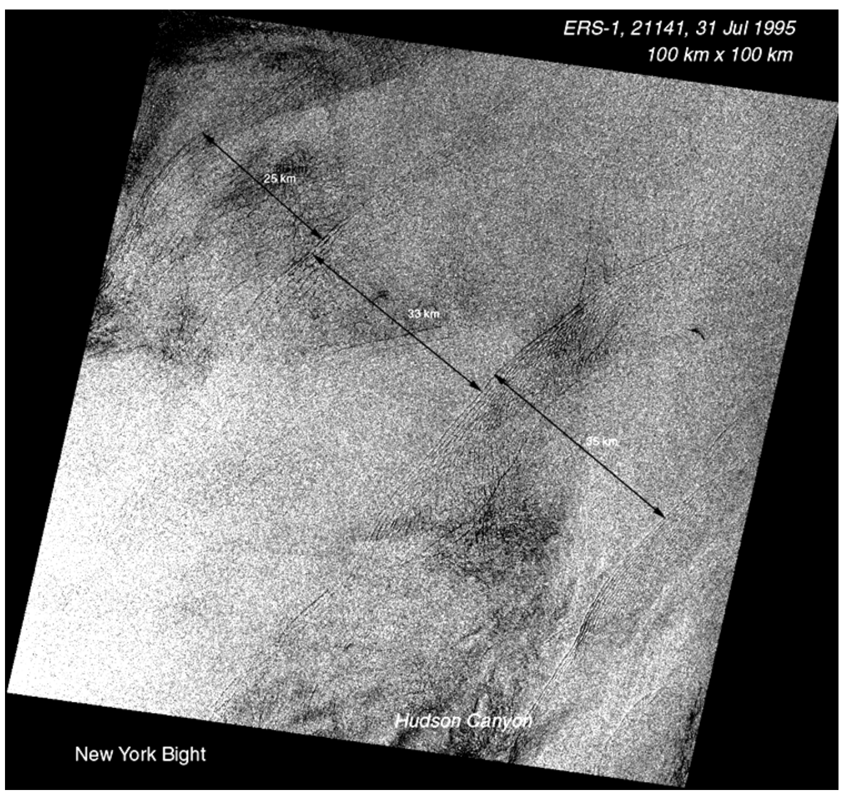

Figure 2. ERS-1 synthetic aperture radar image for the New York Bight., 31 July 1995, showing four packets of internal solitary bores propagating towards shore. Distance between packets is the wavelength of the nonlinear internal tide on the shelf. The Hudson Canyon lies near the bottom, and the continental shelf break is near the lower right-hand corner. Image is approximately 100 km on a side. Copyright European Space Agency, 1995.

Work on the internal soliton atlas has produced approximately 11 case studies, including geographical sites at Georges Bank, the New York Bight, the New Jersey Coast, the Yucatan Strait, the Strait of Gibraltar, the Portuguese Coast, the west coast of Africa, the Sulu Sea, the South China Sea, the coast of China off Hong Kong, and the Andaman Sea. The more complete case studies usually contain (1) a SAR or optical image superposed on bathymetric maps, (2) for the site and month, a historical (or occasionally a contemporaneous) density profile, (3) an interpretation of the image giving likely generation regions and other characteristics, (4) estimates of amplitudes and current speeds obtained from the dnoidal model above, and (5) any other modeling or observational information that might be available. Over 100 images of internal solitons are known to the P.I., although only about 60 will be presented in the atlas.

Figure 3 represents an ERS-1 image of Gibraltar showing two sets of solitons, one in an early stage of evolution after its formation near the Camarinal Sill, and another that has moved eastward well out into the Alboran Sea, having been generated on the preceding tidal cycle. Superimposed on the image is a curvilinear orthogonal grid derived from the linear propagation characteristics for the region (G. Watson, private communication). The soliton phase fronts seem to conform to the linear characteristics moderately well. The two-D dnoidal model will be applied along each characteristic shown.

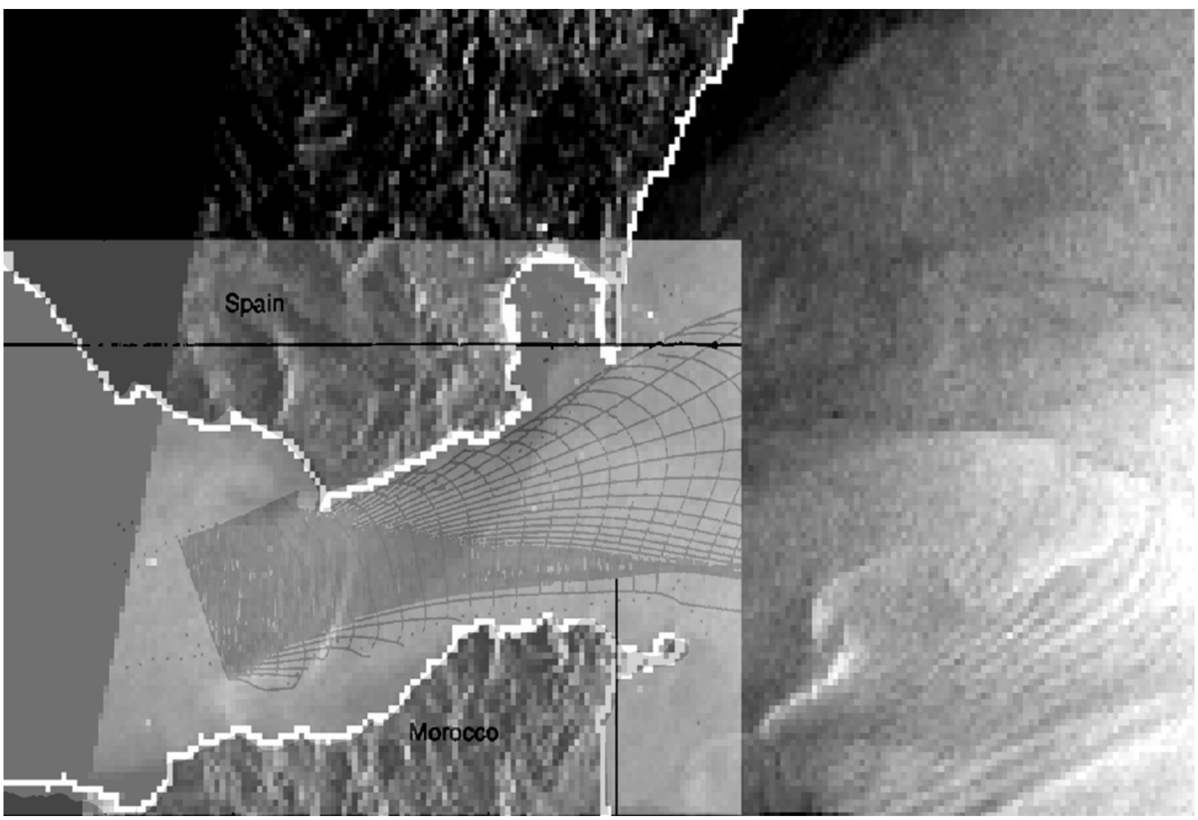

Figure 3. Solitons radiating from Gibraltar, with orthonormal grid of characteristics. Copyright European Space Agency, 1996. Grid courtesy of G. Watson.

A longitudinal study of SAR images of Gibraltar is underway using some 40 images gathered over approximately 2 ½ years. Since the repeat time for the ERS satellites is an exact multiple of 24 hours, and since the tides cycle with periods of approximately 12 ½ and 25 hours, all phases of the tides will be sampled given a sufficiently long time series. The study should show how the solitons depend on tidal forcing throughout the year.

IMPACT/APPLICATIONS

Application of the dnoidal model has been made to the problems of shallow water acoustic propagation. Theoretical studies by Finette and associates (1999) and by Badiey et al. (1999) show the solitons have a profound influence on signals in the 1000-Hz regime, as regards their arrival times, scintillation indices, and mode structure. The influence is especially strong when the acoustic signal propagates parallel to the soliton crests; then the delay time variations become very large and appear to map the soliton waveforms with considerable fidelity.

Solitons impact several other important activities in the shallow-water environment. The currents associated with them are known to disrupt submarine operations, and sonar detection will certainly be affected, not necessarily all for the worse. When the waves approach shallow water, they appear to break and become turbulent, suspending bottom sediments and nutrients and thereby enhancing bioproduction. Their buoyancy and currents have also led to breakage of drill pipes in offshore oil-and-gas-platform operations. Finally, their coherence and ubiquitousness in the ocean allow them to be studied as an important nonlinear hydrodynamic phenomenon that is not confined to the sea alone.

TRANSITIONS

Impacts addressed in the previous paragraph have caused the constituent communities to pay increasingly close attention to solitons as an important process, and the understanding of physical oceanography so gleaned is making its way into the associated disciplines.

RELATED PROJECTS

ONR-sponsored projects related to this effort include the SWARM, PRIMER, and GLOBEC experiments, the upcoming ASIAEX project, and a number of smaller studies focussed on nonlinear hydrodynamics.

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